A PRIMITIVE DARK INCLUSION WITH RADIATION-DAMAGED OLIVINE IN THE NINGQIANG CARBONACEOUS CHONDRITE Michael Zolensky[1], Keiko Nakamura[1], Michael Weisberg[2] and Martin Prinz[2]; [1]SN2, NASA Johnson Space Center, Houston TX 77058 USA; [2]Dept. Earth and Planetary Sciences, American Museum of Natural History, New York, NY 10024 USA

INTRODUCTION: Ningqiang is a unique carbonaceous chondrite, with similarities to the oxidized CV3s, and includes abundant magnetite, awaruite, CAIs, fayalitic olivine and dark inclusions (DIs). It has a somewhat lower refractory lithophile-element content and a higher carbon and H2O abundance [1-3] than typical CV3s. We have examined a large (5mm) Ningqiang DI in order to assess its origin, its relationship to host Ningqiang and to DIs in CV3 and other carbonaceous chondrites. To our surprise this DI indicated a more primitive nature that previously studied DIs and provided a wider window to nebular history.

The DI in Ningqiang was studied by EMPA, SEM and TEM techniques. It was cut, polished and thin sectioned, and two chips of the DI and one of the host rock matrix were ion milled for TEM investigation. Laboratory-derived k-values were used; most analyses are precise to within 3% relative, those for olivine are precise to within 1% relative for major elements.

RESULTS: The DI consists principally of olivine grains, often with anhedral morphologies, and a compositional range from Fo42-62, centered at about Fo50. In contrast, we found that the olivine in adjacent Ningqiang matrix has the range Fo26-65, centered about Fo40. Olivines in Ningqiang chondrule rims, however, have the same compositions as those in the DI [1]. Olivine groundmass grain size in the DI is 10 µm and less. Set within the olivine groundmass are numerous larger subhedral to anhedral, often polymineralic, grains of forsteritic olivine with fayalitic rims, orthopyroxene (En61-98), high-Ca pyroxene (diopside and "augite"), magnetite, Fe-Ni sulfides, and awaruite, all with maximum grain sizes on the order of 10 µm. Some magnetite occurs as framboids with spheres generally 1-2µm, and some up to ~5µm. At the submicron scale additional common phases are hercynite, chromite, and kamacite (~Fe95Ni5). Metal grains are sometimes observed to be rimmed by pyrrhotite. There are also numerous olivine-rich aggregates and CAIs containing Ca-pyroxene, Ca-Al silicates, ilmenite and perovskite, all of which are smaller (<100µm) than those in the host chondrite.

TEM examination shows that much of the finest-grained olivine in the DI consists of fairly euhedral single crystals (Fig. 1); most are completely rimmed by thick (~100 nm) coatings of pyrrhotite-laden amorphous to microcrystalline mafic silicate material. In other places the rimming amorphous material contains dispersed microcrystalline, rounded grains of olivine. In still other places the rims consist entirely of granular olivine and pyrrhotite. In most instances the boundary between olivine and rim mafic material is sharp.

The composition of the amorphous material is generally the same as that of the underlying olivine crystal, and occasionally it is more silica rich, nearing a pyroxene-like composition. The underlying olivine crystals contain numerous inclusions of pyrrhotite, hercynite and chromite, similar to fayalitic olivine in Allende DIs [4&5]. The fayalitic olivine in the Ningqiang host matrix does not have amorphous rims.

DISCUSSION: It is difficult to make olivine glass granules by the cooling of a liquid, since at grain sizes larger than a few tens of nanometers crystallization into something such as enstatite and silica proceeds rapidly (G. Lofgren, pers. comm., 1996). We therefore suggest that the amorphous rims are from radiation damage. Recent studies have demonstrated that partial annealing of radiation-produced olivine glass will produce sharp boundaries [6]. A byproduct of this annealing process for olivine is typically a spinel such as magnetite (we observe hercynite and chromite) +/- silica. Annealing would also explain the numerous spinel and sulfide inclusions in the olivine as being trapped by the advancing olivine re-crystallization front. If the sharply-bounded, euhedral olivines that are amorphous material-coated resulted from partial annealing, then the sharply-bounded rims with granular olivines represent further annealing at some later time or under conditions (unknown) conducive to polycrystalline olivine instead of larger single crystals. Experiments on the radiation amorphitization of olivine have demonstrated a composition-dependent, radiation dose-dependent, critical temperature (Tc) above which recrystallization is inevitable [7]. The presence of amorphous to polycrystalline rims in the Ningqiang DI imply irradiation occurred near Tc, e.g. ~700-800K for an irradiation of 1.5 MeV ions.

CONCLUSIONS: The source of the radiation-damaged olivines is almost certainly the solar nebula. This Ningqiang DI thus appears to record the following processes: (1) Formation (condensation and Fe-enrichment) of olivine crystals in the nebula with compositions of Fo42-62, (2) Irradiation resulting in amorphitization of the olivine to varying degrees, and pyrrhotite formation (was the spinel originally metal at this stage?), (3) Partial annealing resulting in fairly large, euhedral, olivine grains with remnant amorphous sharply-bounded rims, (4) in some cases prolonged annealing resulting in the microcrystalline olivine rims. The latter annealing would have been a natural consequence of irradiation near the critical temperature for olivine.

We note that many chondritic interplanetary dust particles (IDPs) also appear to preserve evidence of an irradiation event, in the form of nm-sized (very small) rounded globules of Glass with Embedded Metal and Sulfides (GEMS [8]). The preservation of the fine glassy structures in the DI, caused by nebular radiation damage, suggests that the DI was added late into the Ningqiang chondrite, post-dating any parent alteration event. The presence of magnetite framboids in the Ningqiang DI, usually associated with hydration in chondrites, is perplexing since the radiation damaged rims would probably not survive a hydration event. The fayalitic-enrichment of the olivine in the Ningqiang DI must have occurred in the nebula since it predates the radiation damage event.

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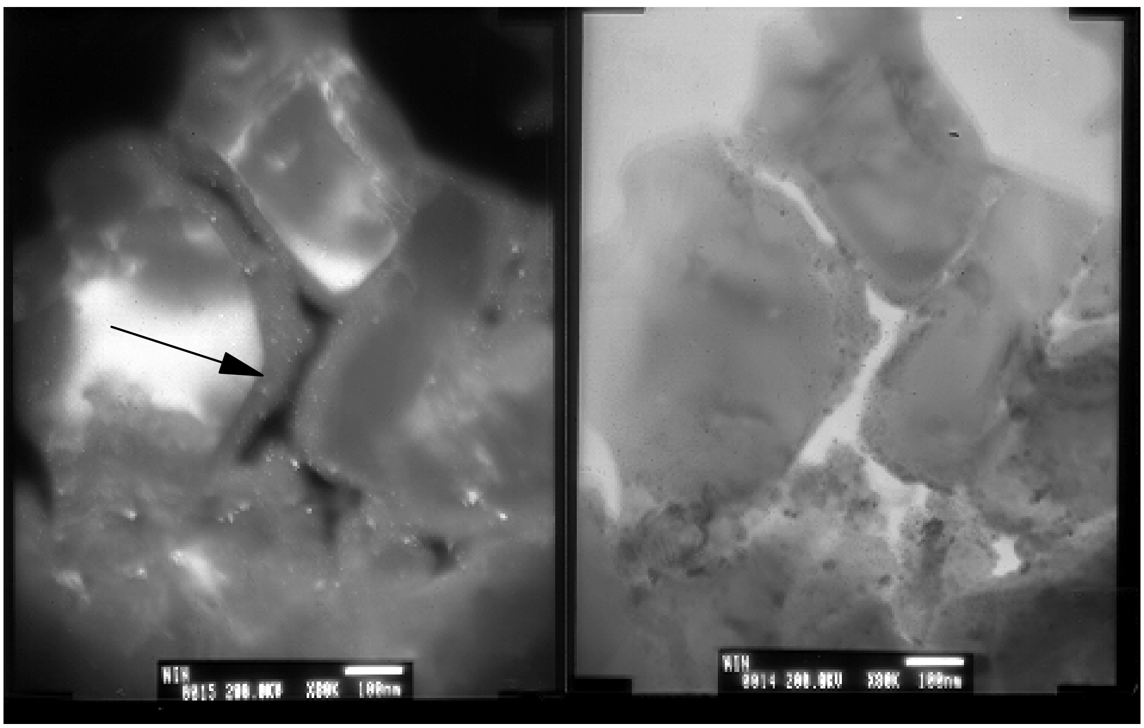

Figure 1: TEM images of Ningqiang DI. (a-left) Dark-field and (b-right) Light-field TEM images of euhedral olivine crystals rimmed with amorphous mafic silicate material (dark and arrowed in the dark-field image) and embedded pyrrhotite (white spots in dark-field). Scale bars measure 100 nm.